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Abstract.—Several studies have investigated the demographics of shovelnose sturgeon Scaphirhynchus platorynchus and pallid sturgeon S. albus in the Mississippi River through assessment of adult populations; however, comparatively few studies have examined the early life history of these species. Here, we describe a comprehensive 4-year study that examined the effects of water temperature and river stage on the mortality, abundance, hatch timing, and growth rates of age-0 Scaphirhynchus spp. sturgeon in the middle Mississippi River. We trawled island areas every 7–10 d from April to August 2004–2007. We captured 1,256 individuals ranging from 10 to 193 mm total length over the 4-year study. Mean age-0 sturgeon growth rates ranged from 1.42 to 1.50 mm/d over the 4 years; however, growth rates did not differ among years. Individuals hatched over a 25–65-d period, and peak hatch dates were between 10 and 20 May in all years. Moreover, hatch timing possibly coincided with optimum spawning temperatures of 17–20°C and an increase in river stage. Abundance appeared to be regulated by river stage; longer durations of high water were related to higher relative abundance. Furthermore, mortality increased with the number of days on which water temperature exceeded 28°C. Based on these data, management strategies may need to ensure sturgeon hatching success and subsequent survival through optimizing hydrologic and thermal regimes that occur during the early life stage.

Most sturgeon populations have declined over the last century, and many are at historically low densities (Pikitch et al. 2005), primarily as a result of the deleterious effects of anthropogenic activities. For example, female sturgeon are disproportionately harvested because of roe demand from the caviar industry. This preferential harvest can reduce overall reproductive potential within a population. Reproductive loss, late age at maturation, and habitat degradation have led to the collapse of multiple sturgeon populations (Billard and Lecointre 2001; Ludwig et al. 2002; Secor et al. 2002; Tripp et al. 2009a).

As a result of declines in sturgeon populations worldwide, the caviar industry has shifted focus from once-thriving anadromous populations (e.g., Caspian Sea sturgeon: beluga sturgeon Huso huso, Russian sturgeon Acipenser gueldenstaedtii, and stellate sturgeon A. stellatus; Billard and Lecointre 2001) to those sturgeon species that reside in large North American

rivers. Specifically, Mississippi River sturgeon appear to have received a substantial proportion of this diverted effort (Colombo et al. 2007). Commercial fishing for the shovelnose sturgeon Scaphirhynchus platorynchus occurs in the middle Mississippi River (MMR), which extends from above the confluence of the Missouri River near St. Louis, Missouri (river kilometer [rkm] 323), to the confluence of the Ohio River at Cairo, Illinois (rkm 0). The rare and sympatric pallid sturgeon S. albus was listed by the U.S. Fish and Wildlife Service as endangered in 1990 (USFWS 1990, 2004). Shovelnose sturgeon may be susceptible to overfishing (Colombo et al. 2007); because pallid sturgeon and shovelnose sturgeon have similar taxonomic traits, incidental bycatch or misidentification of pallid sturgeon is inevitable, and accidental take of this species occurs (Bettoli et al. 2009).

Previous studies have shown that recruitment to adult stages is determined during the early life history in many fishes (Rice et al. 1987), and fluctuations in survival during early life stages can dramatically influence recruitment (Houde 1987). During this critical time period, survival varies until a constant threshold is met. At this point, survival approaches a

constant rate and recruitment to the fishery occurs, thus setting year-class strength. Because of the importance of early life survival and interrelation to year-class strength, much interest exists in understanding fluctuations in early life dynamics (Sammons et al. 2001; Phelps et al. 2008a). Information about the early life history of MMR sturgeon is limited (but see Tripp et al. 2009b), but such information is probably critical for understanding population dynamics.

Factors affecting survival during early life stages are generally size dependent; therefore, growth rate and hatch timing may influence survival (Forney 1976; Post and Prankevicius 1987; Rice et al. 1987). For example, cohort members that hatch earlier than other conspecifics during protracted spawning will have a longer growing season. Consequently, these individuals will probably be larger than later-hatching fish by the end of the first growing season, increasing their likelihood of survival (Cargnelli and Gross 1996). However, other studies have found that later-hatched individuals may demonstrate a compensatory response in growth and thus have higher survival than earlier-hatched members (e.g., Garvey et al. 1998). Furthermore, faster-growing members may achieve size advantages over the slower-growing members of the same cohort (Phelps et al. 2008a), thereby increasing their chances of recruiting. Thus, it is critical to understand the temporal dynamics of sturgeon reproduction in the MMR.

Abiotic factors can affect early life survival (Miller et al. 1988), and several studies have found that water level and temperature influence abundance and subsequent year-class strength in several fish populations (Walburg 1972; Busch et al. 1975; Clady 1976; Phelps et al. 2008b). In riverine systems, Lohmeyer and Garvey (2009) found that larval production of Asian carp Hypophthalmichthys spp. corresponded to temperatures greater than $18\,°C$ and to increased discharge. Specific to sturgeon, Tripp et al. (2009b) demonstrated that adult shovelnose sturgeon reproduction was triggered by an increase in river stage (where river stage was above 6 m) and temperature; however, whether larval sturgeon persisted after this apparent abiotic trigger was unclear. High water is likely to flood riparian areas, which may increase suitable nursery habitat and ultimately increase sturgeon reproductive success (Coutant 2000). Tripp et al. (2009b) noted that successful sturgeon reproduction requires temperature to be within the apparent thermal optima for sturgeon (i.e., $16.9–20.5\,°C$). Temperatures exceeding $28\,°C$ may lead to increased mortality (Kappenman et al. 2009).

In this study, we examined how water temperature and river stage affect relative abundance, growth, and mortality of wild age-0 Scaphirhynchus spp. sturgeon in the MMR. In addition, we explored how water temperature and river stage affect hatch timing. We predicted that years of high discharge with temperatures in the range of optimal growth would create the strongest age-0 sturgeon cohorts.

Methods

Sampling.—Age-0 sturgeon (distinguishing pallid sturgeon and shovelnose sturgeon was not possible due to their similar morphology, but the ratio was estimated as 1 pallid sturgeon larva per 100 shovelnose sturgeon larvae; Schrey 2007) were collected using a mini-Missouri trawl in the MMR (rkm 323 to rkm 0) during April through August 2004–2007 (see Herzog et al. 2005 for complete gear description). Bottom-contour trawling at depths of approximately 2–10 m was completed near island areas throughout the MMR. The number of sampling sites was based on island size (approximately 10 trawls/island). Island sites remained fixed throughout the duration of our study to reduce among-site variability in catch rates of young sturgeon. Sampling was conducted at each site every 7–10 d, with trawl runs lasting 3–10 min. Trawl contents were sorted, and all age-0 sturgeon were measured for total length and stored in a 70% ethanol solution for further analyses. Relative abundance of age-0 sturgeon (catch per unit effort [CPUE]; number of age-0 sturgeon per 100 m^3) was estimated for each trawl. For each sampling event, surface water temperature ($°C$) was recorded with a Quanta Hydrolab, and river stage data (m) were obtained from the U.S. Geological Survey. All trawls for a given year were pooled across sites because previous research in the same reach of the MMR indicated a lack of differences in CPUE among island sites (Phelps et al. 2008c).

Age-0 sturgeon growth rates and age were calculated for each year by the method of Braaten and Fuller (2007). Growth was assessed by combining similar-size (i.e., total length) sturgeon into their respective cohorts over time (i.e., monitoring a cohort over time through length-frequency analyses). Mean length of each designated cohort was regressed against sampling date to determine a cohort-specific growth rate. Using the growth rates for each individual cohort, we determined sturgeon age by use of the following equation:

$$Age\,(d)$$

$$=\frac{(total\ length\ at\ capture;\ mm)}{}$$

$$\frac{-\ (9.03\ mm;\ i.e.,\ sturgeon\ length\ at\ hatch)}{(cohort\ specific\ growth\ rate)}.$$

The resulting age for each fish was then used to determine hatch duration. Catch curves were also

constructed to evaluate instantaneous mortality rates (Z; Maceina 1997) based on 5-d intervals.

Statistical analyses.—Before statistical analyses, CPUE data were $\log_{10}(x + 0.1)$ transformed. A one-way analysis of variance (ANOVA) was constructed in the Statistical Analysis System version 9.1 (SAS Institute, Cary, North Carolina) to determine whether differences in CPUE existed between years. Tukey's post hoc honestly significant difference test was used to determine pairwise differences between years. Mean growth rates were compared between years by using ANOVA. Values of Z based on 5-d intervals were compared by using a homogeneity of slopes test (test for interaction in analysis of covariance). Mean CPUE abundance estimates were correlated with river stage (number of days on which river stage was above 6 m) each year (April 15–July 15) using Pearson's product-moment correlation analysis. Pearson's correlation analysis was also used to evaluate the relationship between Z and the number of days on which water temperatures exceeded 28°C during April 15 through July 15 for all 4 years of the study.

Results

We captured 1,256 age-0 *Scaphirhynchus* spp. sturgeon ranging from 10 to 193 mm total length over the 4-year study. Sturgeon were captured from early April through August in each year. There were differences in average CPUE among years ($F = 30.28$; $df = 3, 1{,}218$; $P < 0.0001$; mean CPUE $\pm$ SE $= 1.07 \pm 0.004$ fish/100 m^3 for 2004, 0.98 ± 0.002 fish/100 m^3 for 2005, 0.15 ± 0.005 fish/100 m^3 for 2006, and 1.19 ± 0.006 fish/100 m^3 for 2007). Pairwise differences were also detected in mean CPUE between years, with density being lowest during 2006 (Figure 1).

Growth rates were based on weekly cohorts in each year (Figure 2). Overall growth rates generated for individual cohorts across years ranged from 0.82 to 2.18 mm/d; the mean ($\pm$ SE) growth rate for the entire study was 1.47 ± 0.07 mm/d. No differences in mean growth rates occurred among years ($F = 0.51$; $df = 3$, 24; $P = 0.68$). The mean ($\pm$ SE) growth rate was 1.42 ± 0.02 mm/d in 2004, 1.5 ± 0.02 mm/d in 2005, 1.49 ± 0.07 in 2006, and 1.48 ± 0.04 mm/d in 2007.

The relative age of sturgeon captured by trawling at all sites ranged from 4 to 85 d. According to these data by year, the coinciding Z-values (based on 5-d intervals) were 0.27, 0.49, 0.64, and 0.25 for 2004, 2005, 2006, and 2007, respectively. Differences existed among years for the majority of pairwise comparisons; the exception was the comparison between 2004 and 2007, which had very similar Z (Figure 3). Note that these rates may have been influenced by size-
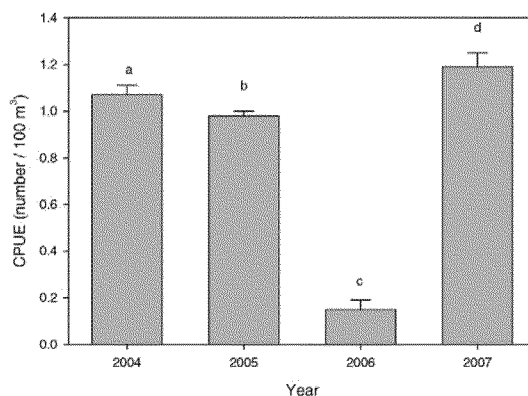

FIGURE 1.—Mean ($\pm$SE) catch per unit effort (CPUE) for age-0 shovelnose sturgeon and pallid sturgeon during 2004–2007. Different letters above vertical bars represent significantly different mean catch rates between years.

dependent avoidance of the gear. However, in both 2004 and 2007, large and relatively old (i.e., > 70 d) individuals were captured in our trawls, which suggests that large individuals present in the sample area were not able to avoid our sampling gear.

Sturgeon hatched over a 25–65-d period (i.e., protracted spawning), and peak hatch dates were similar among years, occurring primarily during 10–20 May. Hatch timing possibly coincided with previously reported spawning temperatures ranging from 17°C to 20°C and occurred with an increase in river stage (Figure 4). Moreover, relative abundance of sturgeon increased as the number of days on which river stage exceeded 6 m increased ($r = 0.79$, $P = 0.003$), suggesting that high water was related to reproductive success. For example, during the 2006 spawning season, the MMR never experienced high water and the lowest relative abundance among the four study years was observed. However, during 2007, flood stage was exceeded for the longest duration, and this corresponded to the highest relative abundance observed in this study. Mortality increased with the number of days over 28°C across years ($r = 0.83$, $P = 0.004$). During 2005 and 2007, water temperatures never exceeded 28°C and Z during those years was low (< 0.30); during 2004 and 2006, however, water temperatures exceeded 28°C and Z was much higher (> 0.49).

Discussion

Among-year variation in early life dynamics of shovelnose sturgeon and pallid sturgeon appears to be due in part to abiotic differences (although growth did not vary across years). Sturgeon reproduction in the MMR was protracted and appeared to be loosely

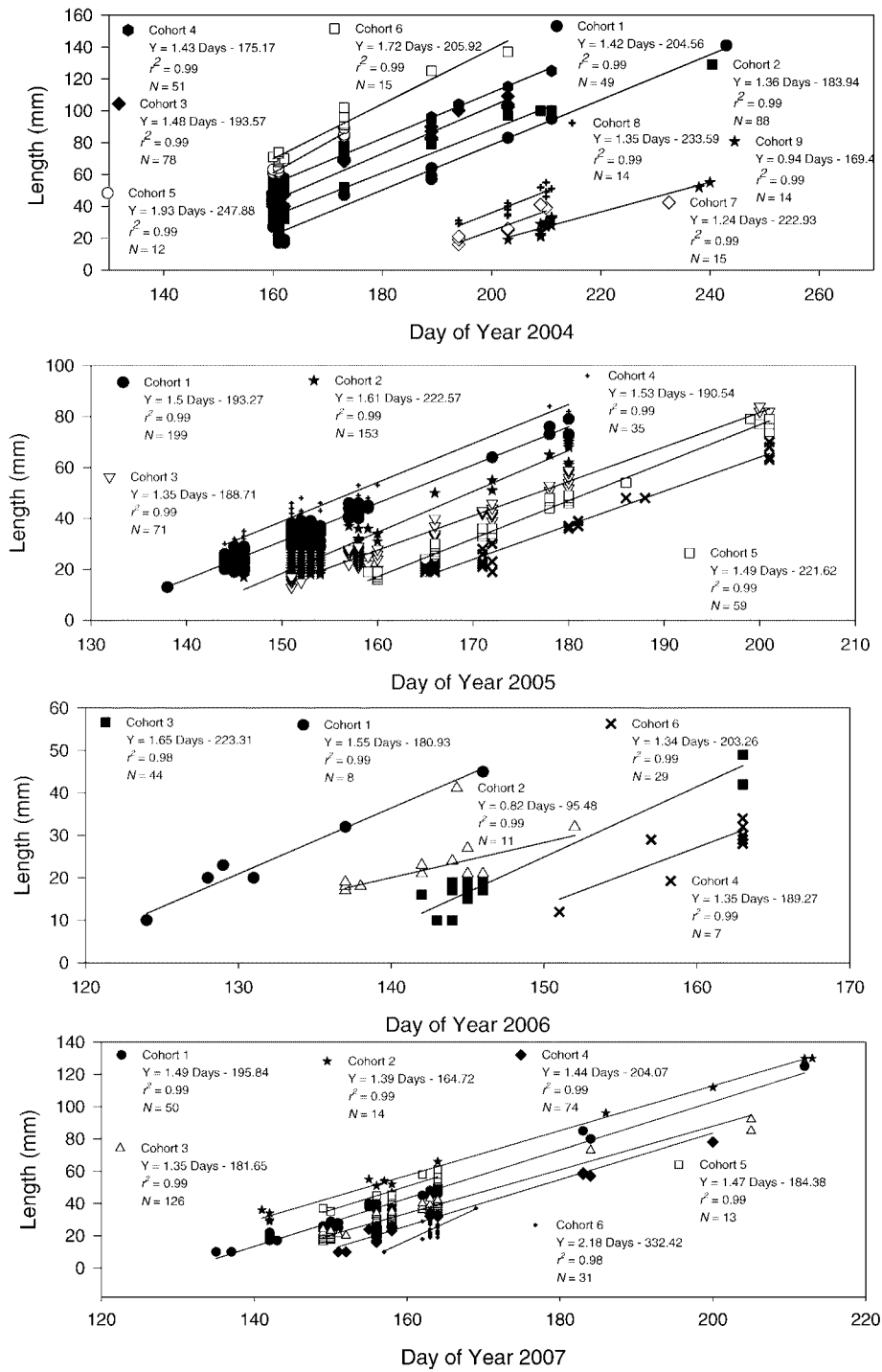FIGURE 2.—Relative daily growth (total length, mm) of age-0 shovelnose sturgeon and pallid sturgeon captured during 2004–2007 in the middle Mississippi River.
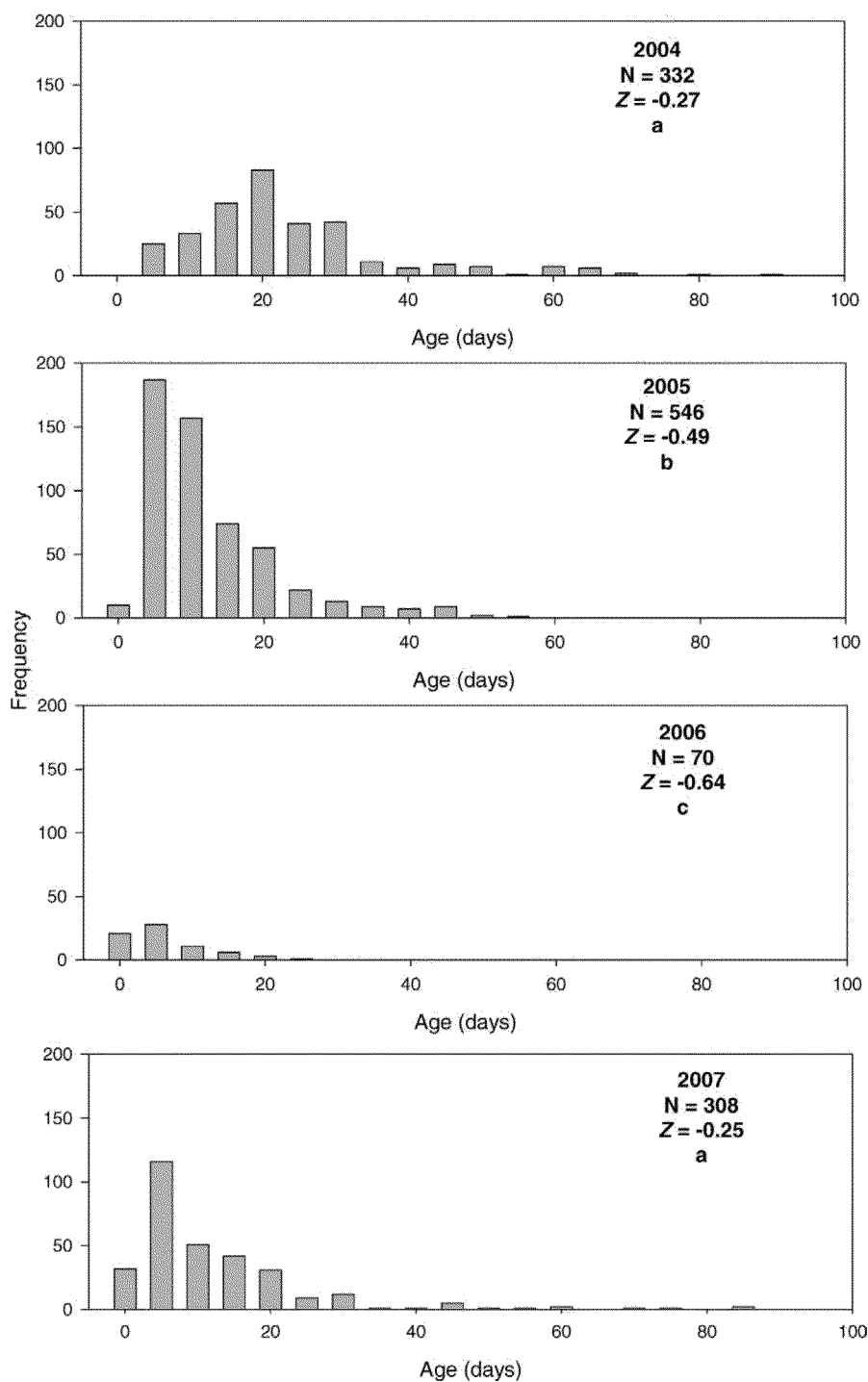
FIGURE 3.—Age (d) of age-0 shovelnose sturgeon and pallid sturgeon captured during 2004–2007 in the middle Mississippi River (Z ¼ yearly instantaneous mortality slopes based on 5-d intervals; letters represent significant differences between years).
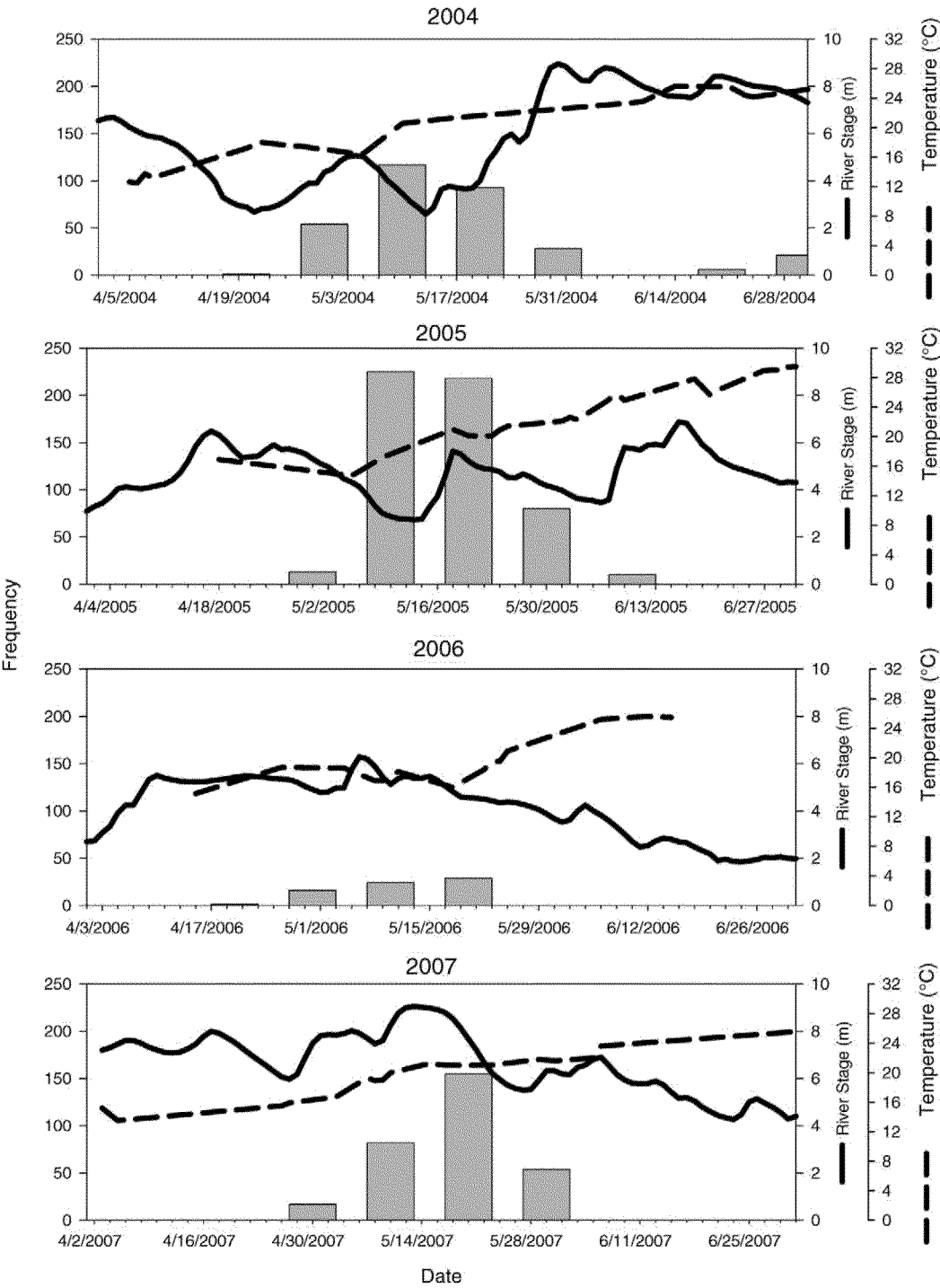
FIGURE 4.—Duration of shovelnose sturgeon and pallid sturgeon hatching plotted in relation to temperature (solid line) and river stage (dashed line) in the middle Mississippi River, 2004–2007.

related to spawning temperatures and to a slight increase in river stage. Similar trends have been shown for Asian carp in this reach of the MMR (Lohmeyer and Garvey 2009). Furthermore, high water (6-m river stage, where dikes and terrestrial vegetation are inundated) throughout the spawning season seems to regulate relative abundance of age-0 sturgeon by year. More specifically, extended periods of high water resulted in greater abundance of young sturgeon. The number of days of high water may be related to an extended period of time for finding adequate spawning locations when temperatures are in the normal spawning range. Thus, sturgeon may spread reproduction across multiple weeks (i.e., protracted spawning period) to ensure some survival of newly hatched sturgeon (see Garvey et al. 2002 for general discussion). Furthermore, flooding of riparian and island areas and their corresponding terrestrial vegetation probably increases the amount of suitable nursery habitat for newly hatched sturgeon. Correspondingly, Coutant (2000) hypothesized that reproductive success of white sturgeon A. transmontanus was intimately tied with inundated riparian habitat.

Temperature may play a key role in survival. During 2005 and 2006, posthatch temperatures exceeded $28°C$, which coincided with the highest Z-values noted during this study. In contrast, during 2004 and 2007, temperature never exceeded $28°C$ during the posthatch interval and the Z of these individuals was lower. Similar to the results of our study, S. R. Chipps and colleagues (South Dakota State University, unpublished data) found that optimum temperature for growth of age-0 pallid sturgeon was between $25°C$ and $28°C$. Likewise, another study by Kappenman et al. (2009) showed that total mortality of age-0 shovelnose sturgeon was lowest at 14, 16, and $18°C$ and that the highest mortality occurred between $28°C$ and $30°C$. The present study has demonstrated that sturgeon reproduction appears to be regulated by river stage, whereas Z may be regulated by temperature.

This is among the first documentation of reproductive success of MMR sturgeon (but see Hrabik et al. 2007; Tripp et al. 2009b) and the effects of abiotic mechanisms that may influence sturgeon during the larval and juvenile life stages. Given that the early life histories of shovelnose sturgeon and endangered pallid sturgeon probably coincide, we need to concentrate effort on understanding the linkages between early life history and adult demographics given previous research suggesting that such a link occurs (Colombo et al. 2007). Further, given the apparent large decline in relative abundance of young sturgeon during the first year of life, we need to determine the extent to which this is caused by gear avoidance, emigration or immigration, changes in habitat location, or actual mortality. Presumably, changes in habitat use as well as survival patterns may be affected by body size. For example, larger juvenile sturgeon may begin to move into habitats that are more closely associated with the main channel and beyond our sampling reaches. In addition, implanting transmitters in larger juveniles may be useful for identifying patterns of habitat use and perhaps dispersal. Controlled releases of marked sturgeon representing multiple size-classes at various locations—conducted in combination with intensive sampling—also may provide insight into size-dependent patterns of catchability and habitat use in the MMR (see Garvey et al. 1998 for a similar approach in reservoir systems).

Management Implications

Sturgeon recruitment variability and recent population declines in many North American ecosystems have increased management efforts to improve or maintain populations (Colombo et al. 2007; Tripp et al. 2009a). This study has furthered the understanding of early life ecology of two large riverine sturgeon species. Furthermore, our findings will assist biologists studying the Missouri and Mississippi rivers in providing management guidance regarding Scaphirhynchus spp. sturgeon reproductive and early life information. Specifically, this study has shown that sturgeon reproduction occurs across a range of conditions, including low-water years and high-water years when temperatures are optimal. Even though recruitment did occur during all years of our investigation, more recruitment occurred during high-water years when temperatures were within the previously reported spawning temperature range (see Tripp et al. 2009b). As such, management strategies may need to ensure survival through optimizing hydrologic and thermal regimes during the early life stage of shovelnose sturgeon and pallid sturgeon.

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